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Combined Heat and Power [DRAFT v3 – Steering Committee Review]

The Uniform Methods Project: Methods for Determining Energy Efficiency Savings for Specific Measures

Created as part of subcontract with period of performance September 2011 – July 2016

George Simons
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July 2016

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Acronyms

BTU	British thermal unit
CHP	Combined Heat and Power
COP	Coefficient of performance
FC	Fuel cell
GHG	Greenhouse gas
GT	Gas turbine
HHV	Higher heating value
ICE	Internal Combustion Engine
IPMVP	International Performance Measurement and Verification Protocol
kWh	Kilowatt-hour
LHV	Lower heating value
MBtu	Thousands of Btu
M&V	Measurement and verification
MT	MicroTurbine
MW	Megawatt
NREL	National Renewable Energy Laboratory
RMS	Root mean square
ST	Steam turbine

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1 Measure Description

The main focus of most evaluations is to determine the energy savings impacts of the installed measure. This protocol defines a Combined Heat and Power (CHP) measure as a system that sequentially generates both electrical energy and useful thermal energy[1] from one fuel source at a host costumer's facility or residence. This protocol is aimed primarily at regulators and administrators of ratepayer-funded CHP programs. However, project developers may find the protocol useful in understanding how CHP projects are evaluated.

The protocol provides a comprehensive method for estimating impacts from CHP systems. For example, in addition to providing ways to estimate electricity impacts, the protocol also includes algorithms and techniques for assessing CHP fuel impacts and calculating several performance metrics for installed CHP systems. Not every evaluation will need to estimate these performance metrics. In addition, some evaluations may lack data needed to conduct more in-depth evaluations. Where such data are missing, the protocol provides default values that can be used in developing impact estimates. To assist evaluators, the protocol also provides flow charts to help determine which equations should be used in estimating impacts. Evaluators should adopt the level of rigor that matches particular evaluation needs and the available data.

For decades, CHP systems sized at 20 Megawatts (MW) and larger have been widely used in the steel, chemical, paper, and petroleum-refining industries. More recently, smaller CHP systems sized to help meet customer energy needs are being deployed at university campuses, in the food and health industries, and at commercial buildings. This protocol focuses on smaller CHP systems used to meet on-site energy needs and generally sized at under 5 MW in rated electrical generating capacity.

In general, CHP systems are installed to help reduce energy costs by offsetting electricity and other fuel purchases. They partly achieve these cost savings through increased efficiency. Due to the integration of both power generation and thermal energy recovery, CHP systems can be significantly more efficient than separate heat and power generating systems.

Figure 1 shows a generalized configuration of a CHP system in comparison to separate heat and power systems.[2] Under a separate heat and power system, electricity is provided to the host site from the grid while a boiler, fueled by purchased fuel, provides heat for onsite heat loads. In some instances, heat loads can include absorption chillers to provide onsite cooling needs. In comparison, the CHP system uses purchased fuel to power a prime mover that generates electricity. Heat released from the prime

[1] Useful thermal energy refers to thermal energy recovered from the CHP system and used to displace thermal energy loads at a host site. Not all heat output from the prime mover can be assumed to be useful heat. Because thermal energy loads can vary, thermal energy available from the CHP system may sometimes exceed the thermal load at the site.

[2] Grid generation can occur in a variety of configurations with associated electrical efficiencies. We use a range of central station power plant efficiencies of 30% to 55% electrical efficiency as being representative. We also use a natural gas-fired combined cycle system to represent the grid because these systems are a predominate source of baseload grid generated electricity in the country.

mover is captured in a heat recovery system and used to meet onsite heating and absorption cooling loads.

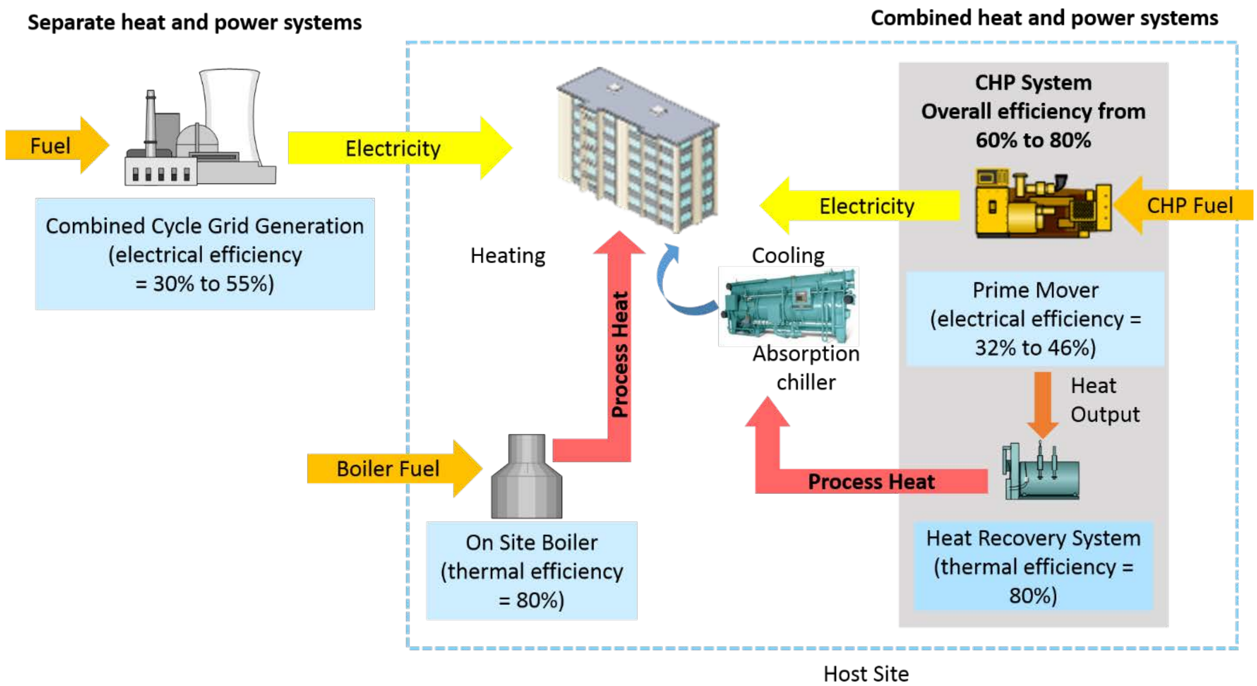

Figure 1. Diagram of Separate Heat and Power vs. CHP

Because CHP savings often coincide with electric utility system peaks, CHP systems can produce significant peak reduction on the grid.[3] This protocol describes common practice methods to account for hourly and annual energy impacts[4] resulting from installation of CHP systems.

While CHP systems can also affect changes in air pollution emissions including greenhouse gas (GHG) emissions, this protocol does not address methods to take into account emission impacts from CHP.

A CHP system consists of a prime mover that consumes fuel to generate electricity and recovers the heat (thermal energy) discharged from the prime mover to produce useful thermal energy. CHP prime movers include a number of different technologies.

[3] In addition, unlike other efficiency measures, CHP systems have the capability to ramp up electricity output, often rapidly. This feature enables CHP systems to be utilized as a dispatchable demand response resource to address system peak needs even when this does not coincide with the host customer's peak demand. As more utilities investigate increased integration of distributed energy resources into grid, this aspect of CHP systems may become important in future evaluation efforts.

[4] We refer to "impacts" here even though other energy efficiency protocols refer to savings. Because CHP projects involve fuel consumption, which may exceed fuel savings, we believe it is more appropriate to refer to energy impacts.

A representative list of CHP prime movers is shown in Table 1. This protocol primarily focuses on natural gas-fueled CHP but includes options to estimate energy impacts for CHP fueled by other sources such as renewable biogas (methane).

Table 1. Representative CHP Prime Movers

Prime Mover	Description	Typical Size Range
Internal Combustion Engine (ICE)	Reciprocating shaft power can produce either electricity through a generator or drive loads directly. Includes both spark ignition and compression ignition engines.	Generally smaller than 5 MW
Gas Turbine (GT)	Gas turbines compress and combust fuel to create hot gases which are routed into the turbine; spinning the turbine blades. The rotating blades spin a generator to produce electricity.	500 kW to 40 MW
MicroTurbine (MT)	Similar to gas turbine in using burner exhaust gases to spin a generator.	30 kW to 250 kW
Fuel Cell (FC)	Produces an electric current and heat from a chemical reaction between hydrogen and oxygen rather than through combustion.	Generally smaller than 5 MW
Steam Turbines (ST)	Converts steam energy from a boiler or heat recovery process into shaft power with a turbine.	50 kW to 250 MW

CHP systems often include auxiliary equipment such as pumps for circulating heat transfer fluids and fans for auxiliary heat rejection. In addition, CHP systems may be connected to other energy processes (e.g., absorption chillers) to increase energy savings to the host site.

The primary drivers of CHP system's electricity and fuel impacts are CHP system efficiencies and utilization:

- **Efficiency** - The effectiveness of fuel conversion and heat recovery in providing electrical and thermal energy services from a CHP system. The two components of overall CHP efficiency are:
  - **Electrical Efficiency** (ratio of net electricity generation to fuel consumption)[5]
  - **Useful Heat Recovery Rate** (ratio of heat recovered and used onsite to electricity generation) (units: MBtu/kWh)
- **Utilization –** The extent to which a CHP system is actually used.[6] This performance driver depends on the percentage of time the system is operating as well as on the degree

[5] Note that electrical efficiency is dimensionless by this definition because energy input and energy output are both the same units

[6] We are using capacity factor as "the unrestricted power output of the system divided by the installed capacity" and utilization as "the actual averaged system power output divided by the installed capacity."

the system operates at rated capacity when running. (i.e., actual annual gross kWh generated/engine rated kW times 8760 hours)

Efficiency and utilization are also parameters that can be used in the evaluation in estimating electricity and fuel impacts.

Table 2 provides a listing of typical operational characteristics such as electrical and overall CHP efficiencies, and maximum useful heat recovery rates.

Table 2. Typical CHP Operational Characteristics[7]

Prime Mover	Electrical Efficiency (HHV)[8]	Overall CHP Efficiency (HHV)	Maximum Useful Heat Recovery Rate (MBtu/MWh)[9]
CE	27-41%	77-80%	4,630
GT	24-36%	66-71%	3,564
MT	22-28%	63-70%	7,839
FC	30-63%	55-80%	2,029
ST	5-40%	near 80%	Not Available

As useful heat recovery rate increases and offsets onsite boiler fuel, it drives up fuel savings. In turn the more that useful heat recovery offsets boiler fuel use over the year, it tends to increase annual fuel savings.[10] Similarly, use of prime movers with higher electrical efficiency results in increased electrical savings through greater displacement of grid supplied electricity. Increased utilization of higher electrical efficiency prime movers drives up annual electricity savings.

However, CHP prime movers consume fuel which affects the overall fuel impacts. Because the prime mover consumes more energy (as fuel) than can be recovered by the heat recovery system, increased utilization of the CHP system tends to increase annual fuel consumption. Lastly, thermal energy recovered by the CHP system may be used to drive an absorption chiller to satisfy cooling load. In this situation, the CHP system offsets operation of an electric chiller and therefore helps reduce electricity consumption.

[7] Electrical efficiencies, overall CHP efficiencies and availability from EPA “Catalog of CHP Technologies,” March 2015, Table 1-3

[8] HHV takes into account the latent heat of vaporization of water in the combustion products. Because CHP systems inherently recover some of this heat in the heat recovery process, we use HHV in reference to efficiencies.

[9] These maximum useful heat recovery rates are based on SGIP 2015 Cost Effectiveness Evaluation; pending. Actual observed useful heat recovery rates may be significantly lower.

[10] Note that fuel savings is decreasing from the top of the pyramid going down. Consequently, as the useful heat recovery increases, it pushes the fuel savings upwards; thereby increasing fuel savings.

The actual performance of individual CHP systems is based on information from input and output energy flows. Typical CHP system components and energy flows are depicted graphically in Figure 2.[11]

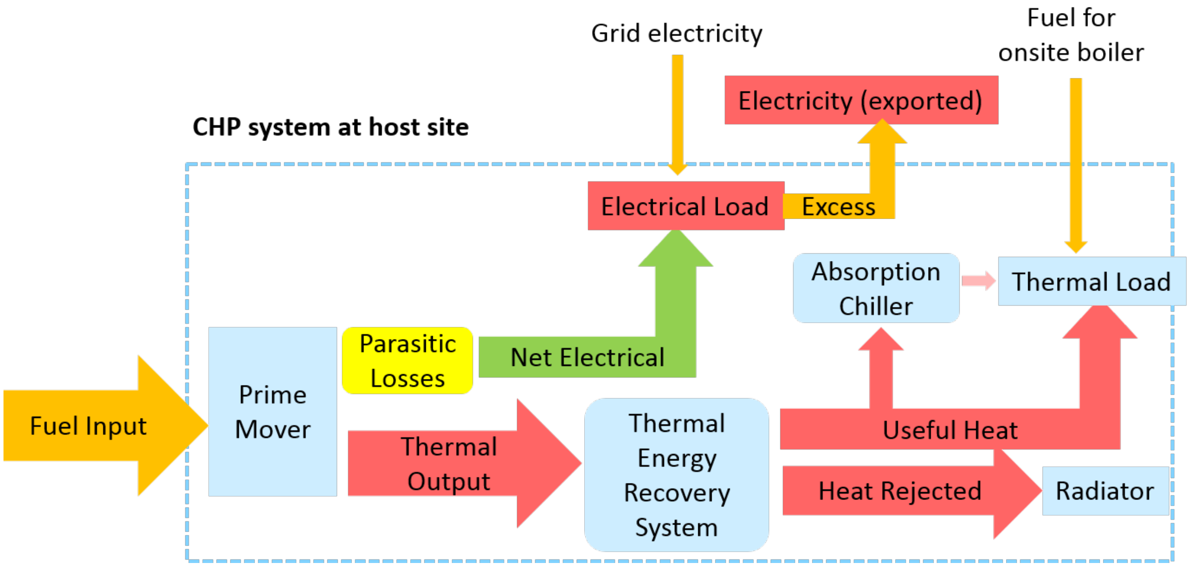

Figure 2. CHP Component and Energy Flow Schematic

The prime mover consumes fuel to produce gross electricity. Parasitic losses reduce the amount of electricity available for actual use (i.e., net electricity). The net electricity serves onsite electrical loads that would otherwise be served by the grid, thereby reducing grid generated electricity required by the customer. In certain instances, electricity generated by the CHP system may exceed the electrical load of the host site and if allowed, the electricity can be exported to the grid.[12] In the course of consuming fuel, thermal energy is generated by the prime mover. A thermal energy (heat) recovery system captures some fraction of the thermal energy generated by the prime mover to serve on-site thermal loads. In some instances, the onsite thermal load may decrease suddenly, and the amount of recovered heat exceeds the onsite load. In those situations, the excess heat is rejected through a "dump radiator". In some instances, useful heat is supplied to an absorption chiller which can offset electricity normally consumed by an onsite electrical chiller or reduce other electrically served cooling loads. By measuring the amount of fuel consumed by the prime mover and the electricity and useful heat supplied to the host site by the CHP system, we can estimate energy impacts from the system.

[11] Parasitic losses can occur with a variety of the equipment associated with the CHP system (e.g., motors and fans for moving fluids or gases). For simplicity sake, we have only referred to parasitic losses as though they are directly associated with the prime mover.

[12] Not all utilities allow CHP systems to export electricity to the grid. However a good example of where this is allowed is under California's Self-Generation Incentive Program (SGIP). Under the SGIP, CHP systems are allowed to export up to 25% of their annual energy demand.

2 Application Conditions of Protocol

Energy-efficiency program administrators may treat CHP systems as a separate and distinct program or may include CHP systems as part of a broader population of commercial, multiunit residential, or industrial custom measures.

Energy efficiency programs that support CHP systems typically provide technical and/or financial assistance to help lower market barriers or help increase customer benefits. Some of these activities may affect the amount of information available for measurement and verification and therefore affect estimated savings. CHP support mechanisms may include the following activities:

- **Prescriptive technology catalogs:** To help reduce costs, accelerate deployment and increase customer acceptance of CHP systems, Program Administrators may develop a catalog of standardized sizes, configurations, and installation methods for CHP systems.[13] Under this approach, programs may only support installation of prequalified and conditionally qualified CHP systems by approved CHP system vendors. Typically, these approaches will also include standardized metering installation methods which can help provide measured performance data on the CHP systems.
- **Training and outreach:** CHP system performance is inherently tied to customer operations and business practices. For example, a business that operates only 8 hours per day, five days a week and has low thermal energy demand will have lower potential for energy savings from use of CHP than a business that operates 24 hours a day, seven days a week and has consistently high thermal energy demands. Program Administrators may provide training and outreach to educate prospective end users about the "fit" of their business to a CHP project. In addition, PAs may offer feasibility studies or software tools to help customers better understand CHP project costs and impacts.[14]
- **Rebates or financial incentives.** Program Administrators such as those in California, Massachusetts, and New York often provide rebates or incentives for customers to install CHP systems that meet specific criteria (i.e., technology type, minimum electrical or system efficiency, etc.). Rebates can be upfront payments paid per unit of installed capacity or performance payments paid out per unit of delivered power or energy. In addition, additional "bonus" rebates may be provided to promote use of special fuels, a higher level of performance or other preferences (e.g., use of equipment manufactured in the state or use of local installation companies).[15]

[13] For example, NYSERDA uses a prescriptive CHP catalog approach in its CHP Acceleration Program. See http://www.nyserda.ny.gov/PON2568.
[14] For example, utilities participating in the Massachusetts CHP program require applicants to use a Benefit Cost Model which takes into account power produced by the CHP system, parasitic losses, quantity and type of fuel consumed as well as fuel displaced and timing of power production and thermal loads. See http://www.masssave.com/~/media/Files/Business/Applications-and-Rebate-Forms/A-Guide-to-Submitting-CHP-Applications-for-Incentives-in-Massachusetts.pdf.
[15] For example, under California's Self-Generation Incentive Program, CHP systems that are powered by biogas fuels receive a "biogas adder," while those CHP systems that are developed by a California

- **Demonstrated Savings.** The protocol gives guidance for estimating demonstrated savings through actual operation and monitoring. Estimating expected savings from design documents are not supported or recommended with this protocol.

This protocol provides direction on how to evaluate impacts from CHP systems using a consistent approach. The protocol is applicable to new CHP systems that are acting as a retrofit to existing boilers. It does not apply to situations where there was an existing CHP system. This protocol only evaluates installed CHP system impacts. It does not address impacts achieved through training or through market transformation activities.

3 Savings Calculations

This section presents high-level gross impact equations that apply to all CHP systems.[16] When evaluating the impacts of CHP systems, both electrical and fuel impacts must be evaluated.

Impacts are all presented on an hourly or finer interval basis.[17] Hourly impacts are summed over the course of the year to calculate annual impacts.

3.1 Determining Electricity Impacts

Note that in some instances CHP projects generate more electricity than can be consumed onsite and may be allowed to export electricity to the grid. Because most other energy efficiency measures do not export electricity, this may be a source of confusion in assessing electricity impacts. For CHP projects, exported electricity should be included in the impacts and noted explicitly. In the following sections, we provide methods for estimating electricity impacts. While a key priority is the estimation of annual impacts, we provide methods that enable hourly impacts to be estimated. Hourly estimates are important in determining the impact of CHP systems on utility peak demand. As peak demand is an hourly occurrence, that requires a method for estimating hourly electricity impacts.

Equation 1a. Hourly Net Electricity Impact

$$\begin{aligned}(Net\ Electricity\ Impacts)_t \\ &= [(Gross\ Electricity\ Generated)_t - (Parastitic\ Losses)_t) \\ &+ (Offset\ Chiller\ Electricity\ Use)_t]\end{aligned}$$

Where:

$(Gross\ Electricity\ Generated)_t$ = Electrical energy generated at hour *t* by the CHP equipment; Units: kWh

supplier receive additional incentives. See "2015 Self-Generation Incentive Program Handbook," http://www.cpuc.ca.gov/NR/rdonlyres/8A5A6665-C6C3-4218-8B9B-B658B89E2387/0/2015SGIPHandbookV4.pdf.

[16] In this instance, we refer to gross savings to distinguish it from net savings that are allocated to a program after accounting for factors such as free ridership and spillover.

[17] In many instances, metered electrical data is collected in 15-minute intervals. Interval data can be aggregated to hourly values.

$(Parastitic\ Losses)_t$	=	Electrical energy losses at hour *t* due to pumps, etc. that are required for CHP operation. Ideally, metering would be setup such that any measured generation is net of parasitic losses, not gross. Units: kWh
$(Offset\ Chiller\ Electricity\ Use)_t$	=	Electrical Energy Offset from electrical chillers at hour *t* if heat from the CHP measure is driving an absorption chiller. Units: kWh

Equation 1b: Onsite Net Hourly Electricity Impacts

$$(Onsite\ Net\ Electricty\ Impacts)_t = (Net\ Electricity\ Impacts)_t - (Exported\ Electricity)_t$$

Where:

$(Exported\ Electricity)_t$	=	Net electrical energy generated by the CHP system at hour *t* which exceeds host site demand.

Note that host site electrical loads may not be known on an hourly basis. In that event, assume that all net electricity generated by the CHP system is consumed at the host site.

Annual net electricity impacts are calculated by summing the hourly impacts for the year.

Equation 2. Annual Net Electrical Impact

$$Annual\ Net\ Electricity\ Impact = \sum_{t=1}^{8760} (Net\ Electricity\ Impacts)_t$$

3.2 Determining Fuel Impacts

Fuel impact is generally calculated as shown in Equation 3. For CHP projects, fuel impact is typically negative, meaning that CHP projects consume more fuel than is recovered. Some projects may use one fuel for the CHP system and offset another fuel for heating. For example, a natural gas fired CHP system may offset an oil fired boiler. Care should be taken to make sure to take into account such cross fuel impacts. Additionally, different fuel costs may apply to fuel offsets and prime mover consumption.

Equation 3. Hourly Fuel Impact

$$(Fuel\ Impact)_t = (Fuel\ Offset)_t - (Fuel\ Consumed\ by\ Prime\ Mover)_t$$

Where:

$(Fuel\ Offset)_t$	=	Reduction in onsite fuel consumption at hour *t* that would have been used for onsite thermal energy needs and is derived exclusively from heat recovered by the CHP system. Units: MBtu (HHV basis)
$(Fuel\ Consumed\ by\ Prime\ Mover\ )_t$	=	Fuel consumed at hour *t* by the prime mover. Units:

MBtu (HHV basis)

If there are multiple fuels, fuel impacts are calculated for each fuel type and then summed to estimate total fuel impacts.

If fuel consumption data are not available, the fuel consumption can be estimated based on electrical generation and efficiency as shown below:

$$(Fuel\ Consumed\ by\ Prime\ Mover\ )_t = \left(\frac{Gross\ Electricity\ Generated_t}{\eta_{EE}}\right)(3412)$$

Where:

$\eta_{EE=}$ = electrical efficiency of prime mover (HHV basis)
3412 = conversion factor 3412 Btu/kwh

Where multiple fuels are consumed and fuel consumption data are not available, fuel purchase and delivery records should be examined to determine percentage blends of the fuels for each period, *t*. The percentages can then be used to determine fuel impacts.

3.2.1 Special fuel situations: use of onsite and directed biogas

Increasingly, CHP systems are being installed in locations—such as wastewater treatment plants, landfills, and dairies—where they can benefit by capture and use of the onsite biogas that is generated by the host site or that is delivered to the site and would have otherwise been vented to the atmosphere or flared. In many of these instances, the host site may have used onsite biogas in a boiler to meet onsite thermal needs but did not generate power. Consequently, installation of a CHP system does not increase fuel consumption for onsite biogas applications. For systems fueled by a mix of fuel and onsite biogas, a calculated or measured ratio should be used to calculate the fuel impact.

Directed biogas refers to biogas that is collected from a landfill, wastewater treatment plant, or dairy facility that may be located far from the facilities that will use the biogas. The procured biogas is processed, cleaned-up, and injected into a natural gas pipeline for distribution. There is no requirement that the directed biogas sold to a host site contain a significant amount of the original biogas and in fact may contain very little (i.e., molecules) of the original biogas. IN this way, directed biogas acts much like a renewable energy credit. The difference is that a natural gas product (i.e., the directed biogas) is sold to customers even though it may contain very inconsequential amount of actual biogas. For these reasons, directed biogas should be evaluated as having the same energy content as natural gas.

3.3 Determining Energy Offset (Baseline Consumption)

Energy consumed and generated by the CHP system on both an annual and hourly peak basis is relatively simple to calculate from metered data. However, a common issue in evaluating CHP systems is to identify and determine the baseline energy being offset by the CHP system. In many CHP applications, the CHP system represents the retrofit to an existing boiler. Consequently, the onsite boiler fuel consumption represents the thermal energy baseline which will be offset by CHP thermal energy recovery. Similarly, CHP systems are often designed to be sized or operated such that their electricity output approaches but does not exceed onsite electricity demand. As a result, it is common to assume that all electricity generated by the CHP system will offset the onsite electricity loads (i.e., no exported electricity). As identified earlier, some CHP projects are allowed to export electricity. Because exported electricity may still benefit the grid, it is important to account for exported electricity.[18]

CHP projects may also use recovered heat to drive thermally-driven chillers to offset electrical energy that would have been used for cooling. In those instances, baseline chiller electricity demand needs to be taken into account (and can be used to calculate the offset). Likewise, the CHP recovered heat may be used instead of baseline boiler heat to drive previously operating thermally-driven chillers.

Figure 3 shows how production of electricity and thermal energy from a CHP system can be compared to a baseline.

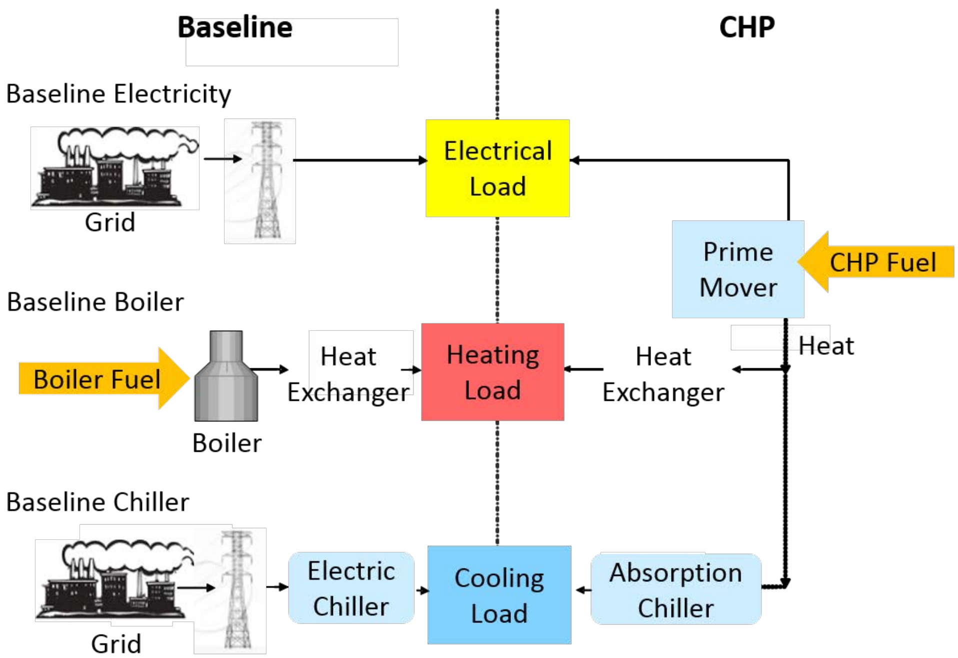

Figure 3. CHP and Baseline Energy Flows

Ideally, site-level data (collected via tracking data or site inspections) are available to identify the boiler, electric chiller, and absorption chiller equipment located at the host site. While this information may provide equipment specifications, it rarely provides data on operating efficiencies. As a result, some estimates of performance and engineering algorithms are usually

[18] It was earlier indicated that where possible the amount of exported electricity should be identified. Because these evaluations can be used as the basis for cost effectiveness studies and exported electricity is valued differently than displaced retail electricity, knowing the amount of exported electricity may provide valuable information.

required to calculate the amount of boiler fuel displaced by CHP heat recovery and electricity displaced by thermally-driven chillers.

Electricity meters should be located such that the metered data explicitly includes the impacts of parasitic loads. However, if this is not the case, parasitic loads must be estimated.[19] The impact of parasitic loads tends to be small (approximately 3 percent of generation) so assumptions about parasitic loads likely have less of an impact on results than sampling error.[20] Another area that often requires approximation is determining the fraction of recovered heat used to offset heating equipment vs. cooling equipment (when an absorption chiller is present).

If actual onsite equipment details are not available, Table 3 provides recommended default values.

Table 3. Recommended Default Assumptions[21]

Parameter	Value	Source
Coefficient of performance (COP) for absorption chillers	0.7 for single effect (default) 1.0 for double effect	ASHRAE Standard 90.1-2010 Table 6.8.1C Water Chilling Packages - Efficiency Requirements (full-load)
Electric chiller efficiency	0.57 kW/ton or matched by size/type	
Higher heating value of natural gas	1,032 Btu/scf	National Energy Technology Lab (NETL) Specification for Selected Feedstock January 2012, DOE/NETL-341/011812
Heating value of landfill gas	Ranges from 350 to 600 Btu/scf (LHV)	EPA Landfill Methane Outreach Program
Heating value of digester gas	Ranges from 600 to 800 Btu/scf (LHV)	EPA AgStar Program
Boiler efficiency	80%	Rough approximation based on minimum efficiencies specified in ASHRAE Standard 90.1-2010 Table 6.8.1F
Parasitic Loads (fan and pump motors, dedicated HVAC and lighting)	90% loaded	Conservative assumption to avoid overstating net electricity, absent spot measurements or metering.
Electrical conversion efficiency	Varies by project and technology (see Table 2)	Project file review, prime mover specification sheet, or average prime mover type efficiencies drawn from industry literature

[19] Spot metering can also be used to determine parasitic loads in some instances but care should be taken to obtain spot measurements at several different operating conditions so as to determine a reasonable estimate of the parasitic losses. Equipment run-time must also be estimated and/or monitored.
[20] Sampling errors occur when CHP systems are looked at in aggregate at the program level.
[21] Note that LHV is used for landfill gas and digester gas as this is the most common reference for heating values for these fuels.

Parameter	Value	Source
Fraction of recovered heat used for heat offsets	1.0 if end use of recovered heat is only heating 0.5 if end use of recovered heat is both heating and cooling 0.0 if all recovered heat is used for cooling	Approximations if no other data are available. If Ex Ante analysis includes division of heat used for cooling vs. heating by season, that division can be re-used here

4 Measurement and Verification Plan

This section contains both recommended approaches to determine CHP energy impacts and the directions on how to use the approaches under the following headings:

- On-Site Inspections
- Vendor and Tracking data
- Measurement and Verification Method
- CHP Performance Data Collection
- Multiple Fuels
- Interactive Effects
- Detailed Procedures

4.1 On-Site Inspections

CHP systems installed as part of an energy efficiency program typically undergo site inspections prior to receiving rebates. Site inspections may be conducted by the evaluation team or by other contractors. Generally, CHP project developers or host site representatives provide pre-inspection data within a program application. Onsite inspections are conducted to verify installation of the CHP system nameplate ratings versus tracking data, check gross and net power and/or thermal energy output at the time of the inspection and collect or coordinate delivery of relevant hourly trend data since the date of regular operation. Site inspection reports should contain:

- Project information (i.e., project name, applicant and host customer name, account number, application number and facility address)
- Schematic of CHP system (including location of all installed meters) and layout of CHP within host site
- One line diagrams for electrical distribution and thermal distribution between the prime mover and the useful loads including rejected energy
- Description of how generated electricity and recovered thermal energy are used at the host site

- Types of metering being conducted at the site and description of meter download procedures (i.e., how often is data downloaded and to what location)

- Presentation of key trend data, as available

During the site inspection, the inspector should confirm that the system is a permanent installation connected to the grid and that the generator (prime mover) and heat recovery system operate as designed.

Table 4 lists representative data collected from site inspections that are important for M&V purposes.

Table 4. Representative Site Inspection Data

Dates	Fuel Sources	Prime Mover Data	Heat Recovery System
Inspection date	Primary fuel source (% of energy input)	Technology type	Recovery system type
Operational date	Flowrate of fuel	Manufacturer	Manufacturer
	Secondary fuel source (% of energy input)	Model number	Model number
	Flowrate of secondary fuel	Equipment Location	Equipment Location
		Prime mover input rate $(MBtu/h)_{HHV}$	Area served with heat recovery
		Prime mover output (kW)	Hours per year of heat recovery service
		Number of prime mover units	Useful heat recovery output (MBtu/hr)
		Total measured power output at inspection (kW)	Inlet water temperature
			Outlet water temperature
			Water flowrate (gpm)

4.2 Measurement and Verification Method

This protocol recommends an approach for verifying CHP savings that adheres to Option A—Retrofit Isolation: Key Parameter Measurement—of the International Performance Measurement and Verification Protocol (IPMVP).

Key parameters that require measurement are net electrical generation (and export), useful heat recovery, and fuel consumption. If metered prime mover fuel consumption is not available, it may often be estimated based on prime mover specification sheets and/or data from similar systems. Typically, CHP systems are installed as retrofits to existing onsite boilers. There is usually no or limited metered data on hourly boiler fuel consumption. This protocol emphasizes metered data collected post-installation of the CHP system and does not include pre-installation data collection requirements.

4.3 CHP Performance Data Collection

To assess energy impacts, data must be collected on CHP performance including the electricity generated and useful thermal energy supplied to the host site. Metered data to be collected include net electricity generated (kWh), net real power delivered (kW), and flowrates and associated inlet and outlet temperatures needed to determine useful thermal energy supplied to the host site.

When using Option A (the preferred approach) to assess CHP systems, the following M&V elements require particular consideration:

- Measurement Period and Frequency
- Measurement Equipment

4.3.1 Measurement Period and Frequency

Metered data is to be collected post-installation. It is important to use measured data only after the CHP system has completed commissioning and shakedown. The amount of time this takes varies but measurements can usually start once the CHP system operation approaches expected operations (i.e., power and thermal output levels) consistently for more than two months. There are two important timing metrics: (1) the measurement periods and (2) the measurement frequency:

- Choose the measurement period (the length of the expected baseline and reporting periods) to capture a full year. This is important in capturing the seasonal impacts of both the CHP system performance and facility operation. If a full year is not available, we recommend capturing at least 6 months of operational (post-installation) data, with at least one month in summer and one month in winter.
- Choose the measurement frequency (the regularity of measurements during the measurement period) to provide at least hourly measurements. If an integrating BTU meter is not used, then more frequent data collection intervals may be warranted.

4.3.2 Measurement Equipment

For the key parameters, data may be collected from existing CHP equipment vendor supplied metering. In the event that the vendor supplied metering cannot provide enough information[22], then the installation of submeters is necessary to obtain data. Use these guidelines to select the appropriate metering equipment and procedures:[23]

- Net Electricity Generation Meters

[22] For example, submetering may be required if the existing thermal metering system does not accurately measure useful heat but instead measures only heat output from the prime mover or does not take into account dump radiators. Similarly, some electrical meters may supply only cumulative energy instead of interval energy.

[23] Further information on choosing meters can be found in the Uniform Methods Project's *Metering Cross-Cutting Protocols*.

- Meters should be located to measure root mean square power output (RMS kW) from the CHP prime mover and ideally after power delivery to all parasitic loads. If not, separate meters or measurements for parasitic loads may be required. Meters should measure net electricity generated (RMS kWh) and net real power delivered (RMS kW).
- Meters should be capable of collecting data at 15 minute interval or better and generate accurate date/time stamp for all collected data points.
- Meters should have the capability to retain collected data in the event of a power outage and should be capable of storing at least seven days of collected data.
- Meters should have an accuracy of ± 0.5% and meet ANSI C-12.20 certification.
- Meters can be onboard or external Interval Data Recording (IDR) meters.
- Where feasible within the budget, meters should have the ability to communicate collected data to outside data collection entities (e.g., PAs).

- Thermal Energy Recovery Meters
  - Flow meters with "Btu computers" should be insertion type turbine meters, magnetic flow meter or ultrasonic flow meters with real time computation and totalizer.
  - Flow meter/Btu computer should have a field verified accuracy of ± 3%.
  - Fluid temperature measurements should be based on temperatures in thermowells or in the flow stream where possible.
  - Flow meters should be calibrated before placed in the field, verified once installed in the field and calibrated at least every two years.
  - Metering points should be located to obtain useful thermal energy provided to the host site, taking into account possible radiator dumps.

Table 5 lists recommended levels of accuracy for the types of metering equipment used for CHP M&V.

Table 5. Recommended Meter Accuracies

Meter Type	Purpose	Accuracy of Meter
Flow or BTU meter	Useful Heat Recovery	± 3%
Power meters	True RMS power (kW)	± 0.5%

4.4 Multiple Fuels

Some projects may consume one fuel in the CHP measure to offset a different heating or cooling fuel. For example, the type of fuel consumed by the prime mover may be different than the type of fuel consumed by the existing boiler. Care should be taken to capture all the impacts of the CHP measure on different fuel sources.

4.5 Interactive Effects

For projects evaluated under option A and that are installed at sites with other efficiency measures, consider how these may interact with the CHP measure. For example:

- A site that installed both a more efficient boiler measure and a CHP system would see no benefits from the new boiler when heating loads were met from the CHP system. In addition, the thermal savings from the CHP system would be reduced somewhat since the boiler efficiency would be higher.

- A site that installed both a CHP system with an absorption chiller and a more efficient electric chiller would get no benefits from the electric chiller when cooling loads are met with the absorption chiller.

4.6 Detailed Procedures

This section presents detailed steps to calculating Equation 1 (Electrical Impacts) and Equation 3 (Fuel Impacts).[24] Some systems may not include all of these parameters, especially absorption chillers, and in rare cases useful heat recovery. The basic components should be directly derived from metered data:

- Electricity Generation: Directly metered electrical generation, ideally metered as net generation
- Useful Heat Recovery: Directly metered

4.6.1 Electrical Efficiency

Electrical efficiency, defined as a measure of how much of the energy in the fuel input is converted to net electricity, is a key parameter for evaluating CHP performance. This efficiency is largely driven by the type and model of CHP prime mover. IC engines tend to be more efficient than microturbines, and larger engines tend to be more efficient than smaller engines. Operating conditions also play a role. In general, the closer to full load a prime mover operates, the more efficient the system is at converting fuel to electricity. For larger installations, installing multiple prime movers [25]permits operators to optimize the full loading of each engine.[26] Mathematically, the electrical efficiency is defined as follows:

[24] It is typical to calculate electricity impacts first and then fuel impacts as it is usually easier to identify anomalies in electricity output. The electricity impacts can then be used to confirm thermal energy and fuel impacts. However, it is possible to calculate fuel impacts first and then electricity impacts.

[25] When multiple prime movers are used in tandem, the equations should take into account the aggregate capacity of the multiple prime movers. However, if the prime movers are arranged to provide redundancy, care should be taken to only aggregate the systems that will be operated in tandem.

[26] Multiple engines are one simple and effective way of optimizing engine operation to meet varying loads. This method, however, must be balanced with expected load profiles, higher efficiencies often associated with larger engines, and many other factors.

Equation 4. Net Electrical Efficiency

$$Electrical\ Efficiency_{Basis} = \frac{(Net\ Electricity\ Generated_{kWh})}{(Fuel\ Input_{MBtu/hr}) \times \frac{1\ kWh}{3.412\ MBtu}}$$

Where:

$Fuel\ Input$ = the fuel consumed by the CHP system; make sure to use HHV *Basis*. Units: dimensionless

4.6.2 Useful Heat Recovery Rate

Useful heat recovery rate (UHRR) is one measure of the effectiveness with which thermal energy is recovered from the prime mover and used to meet onsite thermal needs; either onsite heating loads or onsite cooling loads. System design (e.g., sizing) and the timing and magnitudes of facility electrical and thermal loads play key roles in determining a CHP system's heat recovery rate. Mathematically, the useful heat recovery rate is defined as follows:

Equation 5. Useful Heat Recovery Rate

$$Useful\ Heat\ Recovery\ Rate\ (UHRR) = \frac{Useful\ Heat\ Recovered}{Net\ Electricity\ Generated}$$

Where:

$Useful\ Heat\ Recovered$ = the heat that is recovered from the CHP system and used onsite, units: MBtu (HHV basis)

Note that useful heat recovery rate has units of MBtu/kWh.

4.6.3 Overall CHP Efficiency

Electricity generation and recovered heat are combined to form an overall efficiency to quantify how much of the energy input is used. If a CHP system generates substantial quantities of electricity when facility thermal loads are low, large quantities of heat will be rejected to the atmosphere which will reduce the overall efficiency of the CHP system. Overall efficiency is defined as follows (note the conversions to maintain consistent units):

Equation 6: Overall Efficiency

$$Overall\ Efficiency = \frac{Net\ Electricity\ Generation + Useful\ Heat\ Recovered \times \frac{1\ kWh}{3.412\ MBtu}}{Fuel\ Input\ \times \frac{1\ kWh}{3.412\ MBtu}}$$

4.6.4 Electric Chiller Offset (using Thermally-Driven Chiller)

Some CHP systems use an absorption chiller to convert useful heat to cooling energy. This allows the CHP system to operate in summer. Equation 7 shows how this electrical cooling offset should be calculated

Equation 7. Electrical Energy Offset$_{\text{Chiller}}$

$$ElectricityOffset_{Chiller} =$$

$$\text{Net Electricity Generation} \times UHRR_C \times COP \times \left(EffElecChlr \frac{kWh}{ton-hr\ of\ cooling} \right) \left(\frac{ton-hr\ of\ cooling}{12\ MBtu} \right)$$

Where:

$ElectricityOffset_{Chiller}$	=	Electricity a power plant would have needed to provide for a baseline electric chiller. Units: kWh
$NetElectricityGeneration$	=	Net electrical energy generated by the CHP system. Units: kWh
$UHRR_C$	=	Useful heat recovery rate that is used to drive an absorption chiller. Units: MBtu/kWh
COP	=	Coefficient of Performance of the absorption chiller. Unitless
$EffElecChlr$	=	Efficiency of the baseline electric chiller. Units: $\frac{kWh}{Ton-hr\ of\ cooling}$

Equation 8. Fuel Consumption

$$Fuel\ Impact = Fuel\ Offset - Fuel\ Consumed$$

$$= \frac{Net\ Electricity\ Generation \times UHRR_H}{Boiler\ Efficiency} - \frac{Net\ Electricity\ Generation}{Net\ Electrical\ Efficiency} \times \frac{3.412\ MBtu}{1\ kWh}$$

$$= Net\ Electricity\ Generation \times \left[\frac{UHRR_C}{Boiler\ Efficiency} - \frac{1}{Net\ Electrical\ Efficiency} \times \frac{3.412\ MBtu}{1\ kWh} \right]$$

Where:

$Fuel\ Offset$	=	Reduction in fuel consumption that would have been used for heating that can be attributed to the CHP system. Units: MBtu (HHV basis)
$Fuel\ Consumed$	=	Fuel consumed by the CHP system. For Biogas fueled CHP systems, this can be zero. This value can be estimated based on electrical generation and efficiency. Units: MBtu (HHV basis)
$UHRR_H$	=	Useful heat recovery rate that is used to offset onsite heating. Units: MBtu/kWh
$Boiler\ Efficiency$	=	Efficiency of the boiler of other heating equipment that would serve heating loads in absence of the CHP system. Unitless (HHV basis)

4.6.5 Default Assumptions

Where possible, the actual efficiencies of heating and cooling equipment should be used in Equation 3 and Equation 7. If this level of detail is not available, Table 3 provides some recommended default assumptions and the reasoning behind them.

4.7 Overall Approach in Estimating Impacts

Figure 4 provides a series of flow diagrams that can be used to assess the approach used in estimating CHP impacts. The approach can be tailored to the appropriate level of evaluation needs and available data.

Figure 4: Flow Diagram for Assessing Approach

5 Sample Design

At times, evaluators need to assess overall impacts to an energy efficiency program that has multiple CHP systems. If the number of CHP systems is large, it may be cost prohibitive to collect metered data for all the installed systems. In that event, metered data may be collected from a sample of the operating CHP system.

Consult the Uniform Methods Project's Chapter 11: Sample Design Cross-Cutting Protocol for general sampling procedures if the CHP system population is sufficiently large[27] or if the evaluation budget is constrained. Ideally, use stratified sampling to CHP systems by technology, and/or the magnitude of claimed (*ex ante*) project savings. Stratification ensures evaluators can confidently extrapolate sample findings to the remaining project population. Regulatory or program administrator specifications typically govern the confidence and precision targets, which will influence sample size.

6 Other Evaluation Issues

When claiming lifetime and net program CHP measure impacts, consider the following evaluation issues in addition to first-year gross impact findings:

- Early retirement and degradation
- Normalizing CHP Performance
- Net-to-gross estimation

6.1 Early Retirement and Degradation

CHP projects are often expected to last 10 to 25 years.[28] However, over their lifetime, CHP systems can show degradation in availability (which affects capacity factor), electrical or thermal performance from first year operations unless there is a maintenance program in place. In turn, changes in site operations, fuel or electricity prices can result in systems being retired after only a handful of years. Evaluators should therefore take care when estimating lifetime performance from first year savings. That could include persistence studies or leaving metering in place long term to capture savings over time. Programs are strongly encouraged to require ongoing metering of electricity output as a requirement for participation.

6.2 Normalizing CHP Performance

The savings from most energy efficiency measures are correlated to either weather or operating hours. Therefore, most energy efficiency measures can be weather normalized to adjusted

[27] In general, sampling depends on budgetary considerations. However, at the onset of an energy efficiency program where CHP systems are just beginning to be installed, a census is recommended. As the program expands, sampling is recommended when installations of small and same type systems exceeds twenty installations. For larger installations (e.g., 1 MW or greater), energy impacts are significant enough to warrant measurements. In general, sample designs should be set to achieve 90% confidence with 10% precision depending on budgetary constraints.

[28] International Energy Agency, Energy Technology Systems Analysis Programme, May 2010.

weather during the study period to a typical weather period. CHP, however, presents a number of challenges to weather normalize because CHP utilization can be highly variable based on host behavior and other factors. These factors include:

- The cost of fuel (often natural gas),
- The cost of electricity,
- The relationship between the cost of fuel and electricity; i.e., if fuel costs rise in relation to electricity then the CHP system will tend to run less. Conversely, if fuel costs fall in relation to electricity prices, the CHP system will tend to run more
- CHP system maintenance; is the system properly maintained on a regular basis so it is available as wanted?
- Process loads for systems that serve process loads
- Weather for systems that serve heating and cooling loads.

Weather does play a role in CHP operation, but the impact of weather varies site to site in comparison to the other factors listed. CHP host customers can choose to not operate the system and meet their energy needs with more traditional methods. This is quite different than, say, LED lighting or new space conditioning equipment that completely replaces the existing equipment so the host can only chose to not have light or heating/cooling or remove the equipment. Therefore, this protocol recommends against attempting to normalize CHP performance.

CHP utilization over time tends to decrease but the impact of this varies. Figure 5 from the 2010 *Self-Generation Incentive Program Combined Heat and Power Performance Investigation*: "graphically summarizes the most significant performance trends observed in the output data. As percentages of the full rated capacity of the system, each bar shows from top to bottom:

- **Unused capacity while on –**the unutilized capacity of the system during hours that the system is on.
- **Capacity factor –** the utilized capacity of the system.
- **Off, < 1 day duration –** the percentage of all hours that the system has zero output for less than 24 hours at a time.
- **Off, 1 to 3 day duration** - the percentage of all hours that the system has zero output for 24 to 72 hours at a time.
- **Off, > 3 day duration** - the percentage of all hours that the system has zero output for more than 72 hours at a time.

Each vertical bar has a length of 100 percent and represents the potential output of systems if they were running at rated capacity at all hours (24/7). Therefore, the solid black portion of each bar shows the capacity factor, and the other portions of the bar show unutilized potential." [29]

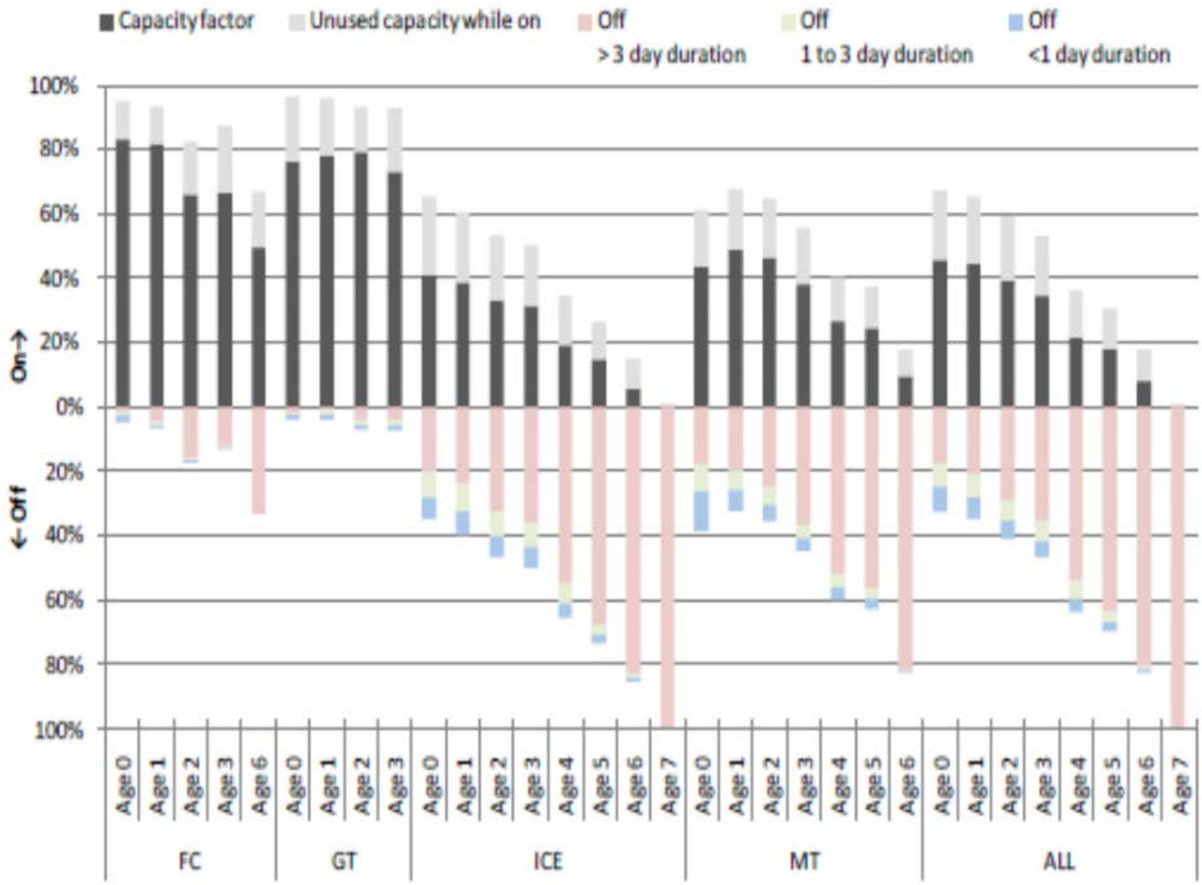

Figure 5. CHP Performance Over Time

As shown in Figure 5, CHP utilization in year 0 or year 1 is often not representative of CHP performance years later. Similarly, Figure 6 shows the portion of CHP capacity online as a function of age for the SGIP program through 2013.[30]

[29] Navigant, Self-Generation Incentive Program Combined Heat and Power Performance Investigation, April 2010

[30] Itron, 2013 Self-Generation Incentive Program Impact Evaluation, April 2015

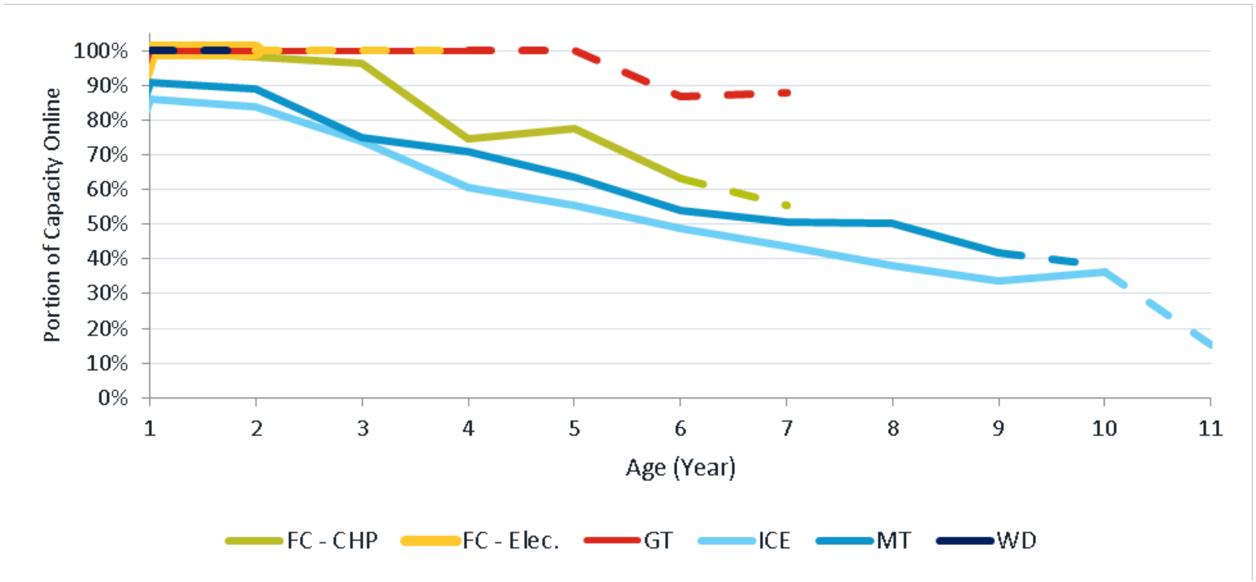

Figure 6. Portion of CHP Capacity Online as a Function of Age

Some technologies like Gas Turbines (GT) tended to remain online longer than others. In the case of gas turbines, this may be due to the fact those tend to be larger and more expensive systems installed with maintenance contractors. The factors that drive systems to go offline (or even be removed) are similar to those that drive utilization. Given the variability of system performance over the years, evaluators should take great care in extrapolating first year performance over the system lifetime. Rather than attempt to extrapolate, energy impacts over the years should be based on metering that remains in place long term.

6.3 Net-to-Gross Estimation

CHP systems are complex; requiring detailed engineering and sometimes significant effort in obtaining air pollution control permits and commissioning to bring the system to expected levels of operation. For these reasons, free ridership and spillover do occur as frequently as for other, more common energy efficiency measures. For some more mature programs, there are some instances where host sites may install CHP systems without use of incentives or install greater capacity than what can be rebated. As programs mature or as the cost effectiveness of CHP systems increases, free ridership and spillover need to be taken into account.

The cross-cutting chapter, *Estimating Net Savings: Common Practices*, discusses various approaches for determining net program impacts. To ensure adjustments to impacts are not double-counted at a population level, follow the best practices that include close coordination between: (1) staff estimating gross and net impact results, and (2) the teams collecting site-specific impact data.

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